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IMPACT TEST METHODS FOR HELMETS
SUPPLEMENT I
TO
HELMET DESIGN CRITERIA
FOR IMPROVED CRASH SURVIVAL

By

J. W. Turnbow

January 1966

U. S. ARMY AVIATION MATERIEL LABORATORIES

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for

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FOREWORD

This supplement on impact test methods is separated from the basic report in order to permit study by readers who are interested primarily in this subject.

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ILLUSTRATIONS

APPROACH TO THE PROBLEM

The following analysis is presented to allow the reader to evaluate the primary methods of testing helmets and to illustrate specifically certain problems associated with each test method in interpreting the test results.

There are essentially three basic impact test methods, although there are many possible modifications of these three basic concepts. These methods employ (1) impact of a movable head-helmet assembly with a movable striking mass, (2) impact of a movable striking mass against a fixed head-helmet assembly, and (3) impact of a movable head-helmet assembly against a fixed anvil. The term "impact testing", as used in this section, implies that blows to one and only one side of the helmet are to be sustained during each impact.

The evaluation and/or comparison of helmet performance against the impact threat must be based upon the measurement of three parameters: (1) head acceleration (2) energy-absorption capacity, and (3) resilience, since the ideal helmet absorbs maximum energy with no resilience (no rebound after impact) while maintaining a tolerable acceleration level (no injury). The test method selected should permit these measurements to be made simply and preferably without bias due to helmet weight and other possible variables unless the measured quantities can be readily and accurately corrected for such bias. The analyses presented in the following sections illustrate the effect of two variables, the mass of the test components, and the coefficient of restitution upon the energy-absorption and acceleration levels.

BOTH HEAD-HELMET ASSEMBLY AND IMPACTOR MOVABLE

This technique has been used in helmet studies by several research groups as recorded in references 16, 17, 18, 19, and 20.* This method can be represented by the model shown in Figure 1. The effect of the mass of any rotating arms or other support mechanisms attached to the masses participating in the impact are eliminated to simplify the analysis.

* See basic report, Helmet Design Criteria for Improved Crash Survival.

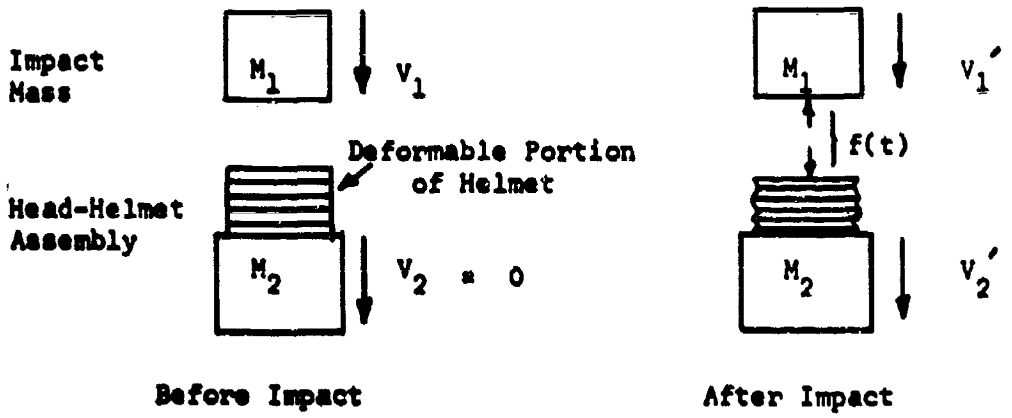

Figure 1. Typical Impact of Two Unrestrained Masses

It is desired to investigate the energy absorbed by the helmet and the acceleration of the head during impact.

Let: M_1 = mass of striker (assumed rigid)

M_2 = mass of head and helmet (assumed a rigid assembly)

V_1, V_1' = velocity of M_1 before and after impact respectively

V_2, V_2' = velocity of M_2 before and after impact

e = coefficient of restitution*

It is assumed in this and all other analyses in this section that the stress (and load) in the deformable portion of the helmet increases monotonically with deformation; thus the maximum compressive force between striker and helmet occurs simultaneously with maximum compressive deformation in the deformable portion of the helmet. Zero relative velocity between the two masses thus also occurs at the time at which this condition exists.

* Discussed on page 7.

Since linear momentum is conserved in the impact of Figure 1,

$$+\downarrow \quad LM_{Before} = LM_{After} : \quad M_1V_1 = M_1V_1' + M_2V_2', \tag{1}$$

also

$$e = \frac{\text{Velocity of Separation}}{\text{Velocity of Approach}} = \frac{V_2' - V_1'}{V_1} \tag{2}$$

Solving these two equations simultaneously gives for the final velocities V_1' and V_2'

$$V_1' = V_1 \frac{\left[\dfrac{M_1}{M_2} - e\right]}{\left[1 + \dfrac{M_1}{M_2}\right]} \tag{3}$$

$$V_2' = V_1 \frac{\left[1 + e\right]}{\left[1 + \dfrac{M_1}{M_2}\right]} \tag{4}$$

Obviously, the velocities after impact depend upon the initial velocity of M_1, the ratio cf the masses, and the nature of the deformable material in the helmet, that is, the coefficient of restitution.

Energy Absorbed. The energies before and after impact are given by

$$KE_B = \frac{1}{2} M_1 V_1^2 \tag{5}$$

$$KE_A = \frac{1}{2} M_1 V_1'^2 + \frac{1}{2} M_2 V_2'^2 \tag{6}$$

Substituting equations (3) and (4) into (6) yields

$$KE_A = \frac{1}{2} M_1 V_1^2 \frac{\left[\frac{M_1}{M_2} + e^2\right]}{\left[1 + \frac{M_1}{M_2}\right]} \tag{7}$$

The energy absorbed by the helmet is thus

$$KE_B - KE_A = \Delta E = \frac{1}{2} M_1 V_1^2 \frac{\left[1 - e^2\right]}{\left[1 + \frac{M_1}{M_2}\right]}, \tag{8}$$

or the fractional part of the initial energy absorbed by the helmet is

$$\frac{\Delta E}{E} = \frac{\left[1 - e^2\right]}{\left[1 + \frac{M_1}{M_2}\right]} \tag{9}$$

where E is the initial energy of the striking mass.

In all three methods of testing, the energy absorbed is p oportional to $\left[1 - e^2\right]$ as indeed it must be in accordance with the basic principles of mechanics. This term in equation (9) is thus not characteristic of the Snell Method of testing only. The term $\left[1 + \frac{M_1}{M_2}\right]$ presents some problem, however, in that a change in either M_1 or M_2 does affect the energy absorbed and thus the damage to the helmet for a given energy input. The effect of this variable factor is shown in Figure 2.

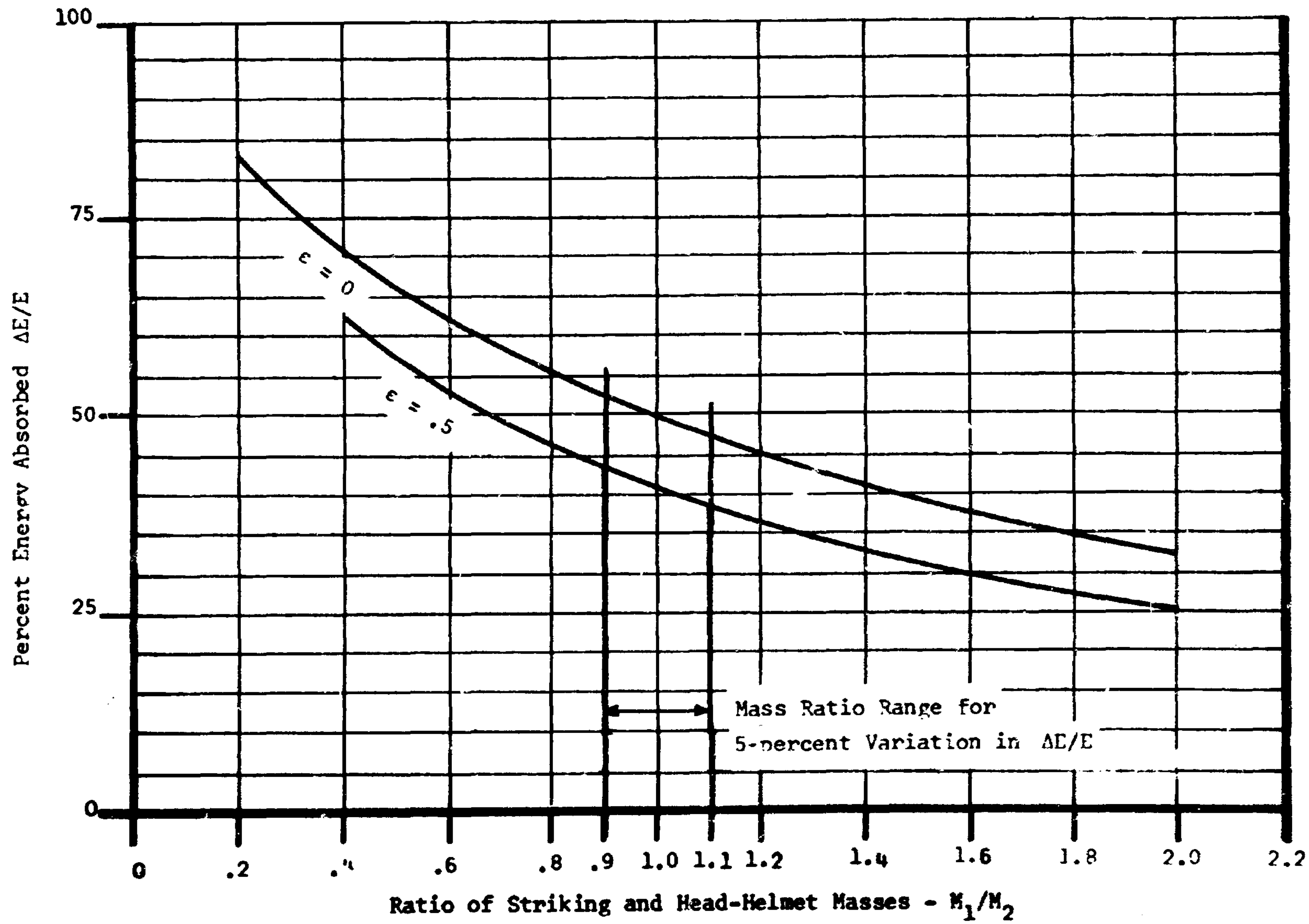

Figure 2. Effect of Mass Ratio on Energy Absorbed.

If the mass ratio is maintained between say 0.9 and 1.0, the effect on energy absorbed is 5 percent above and below the mean. This would allow a variation in helmet weight from 1.4 pounds to 4.6 pounds with a head form of 13 pounds and striking mass of 16 pounds. Thus, the effect is not large if reasonable caution is used in selecting the head and striking masses.

The primary difficulty with this approach lies in the determination of the amount of energy absorbed by the helmet since E in equation (9) is actually an unknown. This test method would require accurate measurement of the rebound velocities of both masses. From these measured velocities, the energy absorbed could then be calculated. In addition, this method does not provide a simple method of obtaining the rebound characteristics (resilience) of the helmet. However, "e" can be calculated from equation (9), or it can be calculated (with generally low accuracy) from the acceleration-time curve obtained from the head, if it is assumed that the helmet compressive load increases monotonically with deflection.

A complete analysis of the acceleration of the head cannot be satisfactorily made until either the force-deflection relationship or the force-time relationship is fixed. Two cases are considered in the following sections in which the force-time curves of Figures 3A and 3B are assumed to apply. These curves are reasonable approximations of those recorded in actual tests, and minor modifications to them will not appreciably modify the conclusions obtained.

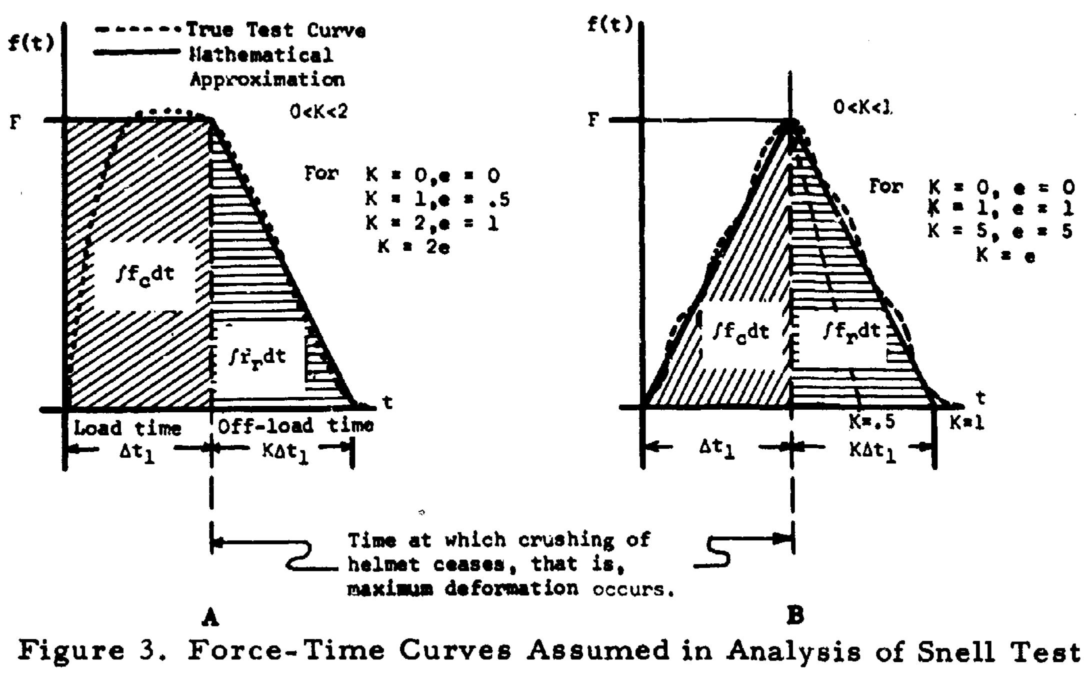

Figure 3. Force-Time Curves Assumed in Analysis of Snell Test Method

The introduction of the factor K as illustrated in Figure 3 permits, in the following analysis, the variation in coefficient of restitution (e) from zero to unity (the maximum possible range). This is done by varying the off-load time as illustrated.

By definition,

$$e = \frac{\text{Impulse During Restitution}}{\text{Impulse During Compression}} = \frac{\int f_r dt^*}{\int f_c dt} \qquad (10)$$

Then, from Figure 3A, it follows that

$$e = \frac{\frac{1}{2} K \Delta t_1 . F}{\Delta t_1 . F} = \frac{K}{2} \qquad (11)$$

For the force-time curve of Figure 3B,

$$e = K \qquad (12)$$

Assuming that the head and helmet are a rigid unit, applying the impulse-momentum principle yields

$$F . \Delta t_1 + \frac{1}{2} F . K . \Delta t_1 = M_2 V_2 \qquad (13)$$

Substituting equation (11) and solving for the time t_1 to compress the helmet to the maximum deformation,

$$\Delta t_1 = \frac{1}{F} \frac{M_2 V_2'}{\left(1 + \frac{K}{2}\right)} = \frac{1}{F} \frac{M_2 V_2'}{(1 + e)} = \frac{M_2 V_2'}{M_2 a_2 (1 + e)} = \frac{V_2'}{a_2 (1 + e)}, \qquad (14)$$

where a_2 is the maximum acceleration of mass, M_2 under the action of the force F, that is,

$$F = M_2 a_2 \qquad (15)$$

---

* It can also be shown that $e = \frac{\text{Velocity of Separation}}{\text{Velocity of Approach}}$

The acceleration, velocity and displacement-time curves are shown in Figure 4 for masses M_1 and M_2.

Since the areas under the velocity-time plot are equal to the displacements d_1 and d_2 for the masses M_1 and M_2, the crushing distance Δ is given by

$$\Delta = d_1 - d_2 = \left[2V_1 - \frac{F}{M_1} \Delta t_1\right] \frac{\Delta t_1}{2} - \frac{F}{M_2} \frac{\Delta t_1^2}{2} \quad (16)$$

Substituting equations (14) and (15) gives

$$\Delta = \left[2V_1 - \frac{a_2 M_2}{M_1} \frac{V_2'}{a_2(1+e)}\right] \frac{V_2'}{2a_2(1+e)} -$$

$$\frac{a_2 M_2}{2M_2} \frac{V_1'^2}{a_2{}^2 (1+e)^2} \quad (17)$$

$$\Delta = \frac{V_1 V_2'}{a_2(1+e)} - \frac{V_2'^2}{2a_2(1+e)^2} \left[1 + \frac{M_2}{M_1}\right],$$

but from equation (4)

$$V_2' = \frac{V_1\left[1+e\right]}{\left[1 + \frac{M_1}{M_2}\right]}$$

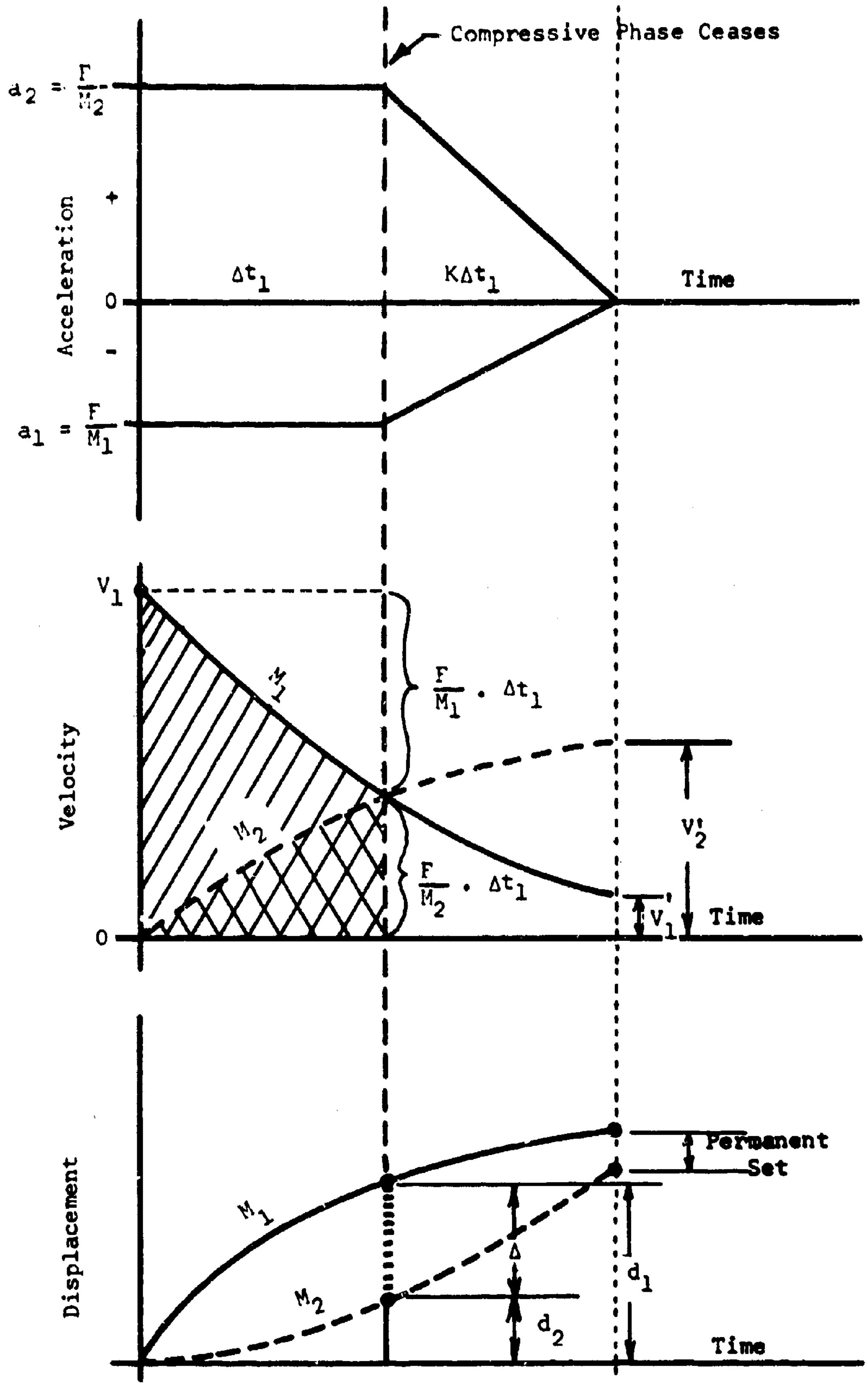

Figure 4. Acceleration, Velocity, and Displacement for M_1 and M_2.

Substituting into (17) and solving for a_2 yields

$$a_2 = \frac{1}{\left[M_1 + M_2\right]} \times \frac{\frac{1}{2} M_1 V_1^2}{\Delta} = \frac{V_1^2}{2\Delta} \times \frac{1}{\left[1 + \frac{M_2}{M_1}\right]} \qquad (18)$$

or since $\frac{M_1 V_1^2}{2}$ = input energy E

$$a_2 = \frac{E}{\Delta\left[M_1 + M_2\right]} = \frac{E}{\Delta M_1 \left[1 + \frac{M_1}{M_2}\right]} \qquad (19)$$

It should be noted that the maximum acceleration "a" of the head-helmet assembly is not dependent upon the coefficient of restitution e as incorrectly reported in some studies; however, it does depend upon the input energy E, the crushing distance Δ, and upon the value of both M_1 and M_2. This has given some investigators concern that this method gives an advantage to the heavier helmet with respect to acceleration measurements. Consider, however, two tests, A and B, in which only the helmet mass varies. From equation (19), it follows that

$$\frac{a_A}{a_B} = \frac{\Delta_B}{\Delta_A} \times \frac{\left[M_{1_B} + M_{2_B}\right]}{\left[M_{1_A} + M_{2_A}\right]} \qquad (20)$$

for equal crushing distances and values of M_1 and M_2 consistent with those used by most testing agencies; that is,

$M_1 \cdot g$ = 16 pounds $\qquad$ $M_{Head\ Form} \cdot g$ = 13 pounds

A variation of helmet weight from 2 pounds to 4 pounds, which is about the maximum range to be expected, gives

$$\frac{a_A}{a_B} = \frac{16 + 13 + 2}{16 + 13 + 4} = 0.94$$

or 6 percent difference. Thus, variation in helmet mass appears to be a relatively insignificant factor.

An analysis similar to the above has been made for the triangular force-time curve of Figure 3B, giving the following results:

$$a_2 = \frac{8}{3} \cdot \frac{E}{\Delta \left[M_1 + M_2 \right]} \tag{21}$$

Again, a_2 is independent of the coefficient of restitution but is sensitive to helmet weight to the extent quoted in the previous example.

It should be noted that for equal input energy

$$\frac{a_2}{a_2} = \frac{8}{3} \times \frac{\Delta}{\Delta} \tag{22}$$

Thus, for equal crushing distances Δ, the acceleration with triangular force-time curve must be 2-2/3 times the acceleration with a rectangular force-time curve during the crushing phase. This graphically points out the desirability of the rectangular force-time relation which implies a helmet material which crushes at as near constant load as possible.

In conclusion, the primary problem in using this test method lies in the determination of the energy actually absorbed by the helmet. It should also be noted in equation (9) that only a maximum of 50 percent of the input energy (for $M_1 = M_2$ and $e = 0$) is absorbed by the helmet in this type test. It is believed that many persons have become confused in evaluating the results of such tests in that they are mistakenly under the impression that the helmet absorbs all the energy reported as input energy. This fact makes it difficult for the layman to compare results obtained by different test methods.

HEAD-HELMET ASSEMBLY MOVABLE , IMPACT SURFACE FIXED

The basic mechanics for this case and the appropriate notation are illustrated in Figure 5.

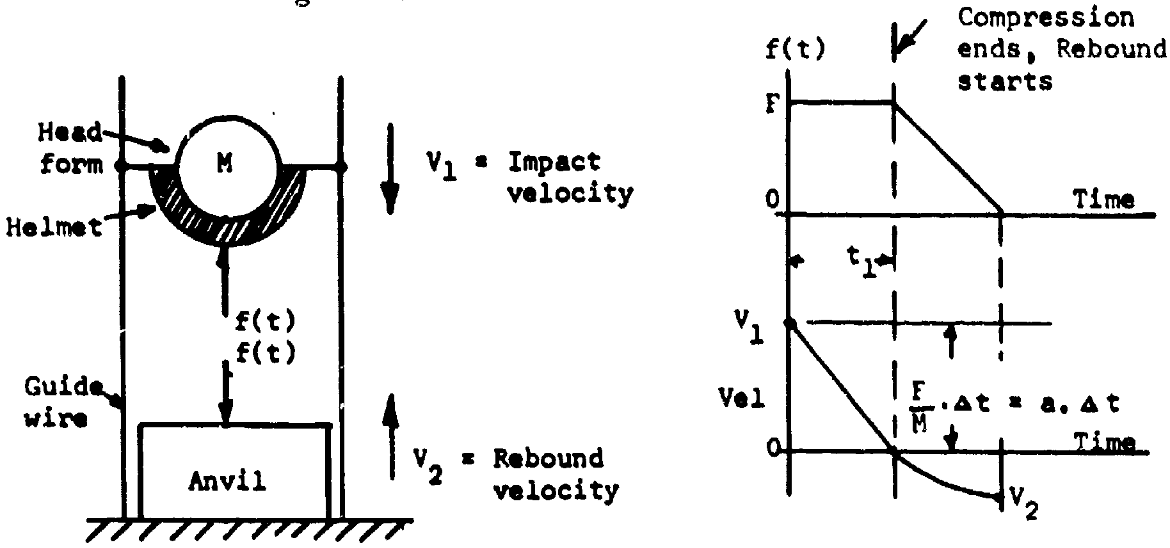

Figure 5. Assumed Force-Time and Velocity-Time Curves for the Analysis of the Impact of Head and Helmet Against a Rigid Anvil.

By definition,

$$e = \frac{V_2}{V_1} \tag{22}$$

$$KE_1 = E = \frac{1}{2} MV_1^2 \tag{23}$$

$$KE_2 = \frac{1}{2} MV_2^2 \tag{24}$$

$$\Delta E = \left[KE_2 - KE_1 \right] \tag{25}$$

Solving for $\Delta E/E$ gives

$$\frac{\Delta E}{E} = \left[1 - e^2 \right] \tag{26}$$

This is identical to equation (9) for the Snell test except for the factor $1/\left[1+M_1/M_2\right]$. For free-fall drop test, V_1 and V_2 can be obtained from the readily measured drop heights h_d and rebound heights h_r, where

$$h_d = \sqrt{2gh_d} \quad \text{and} \quad h_r = \sqrt{2gh_r} \qquad (27)\ (28)$$

The input and final energies are

$$E_1 = E = Mgh_d \quad \text{and} \quad E_2 = Mgh_r \qquad (29)\ (30)$$

Thus, the energy absorbed by the helmet is readily obtained from the equation

$$\Delta E = Mg \left[h_d - h_r \right] \qquad (31)$$

and the coefficient of restitution, if desired, may be calculated from

$$e = \sqrt{\frac{h_r}{h_d}} \qquad (32)$$

These equations (22 through 32) are independent of the shape of acceleration-time curve and of the nature of the materials in the helmet. For the force-time curve chosen in Figure 5, the crushing distance Δ is given by

$$\Delta = \frac{V_1^{\ 2}}{2a}$$

$$\Delta = \frac{MV_1^{\ 2}}{2} \qquad \frac{1}{Ma}$$

$$\text{or} \quad a = \frac{E}{M\Delta} \qquad (33)$$

This result may be compared with equation (19) for the first test method.

Letting M_F be the mass of the head form and M_H be the mass of the helmet, equation (33) can be written

$$a = \frac{E}{\Delta\left[M_F + M_H\right]} \quad , \quad a = \frac{E}{\Delta M_F \left[1 + \frac{M_H}{M_F}\right]} \qquad (34)$$

Thus, even in this method of testing, the heavier helmet has a testing advantage if the criterion is minimum acceleration "a" for a given input energy "E" and fixed crushing distance Δ. It is of interest to note that, in accidents involving head impacts against deformable structure, the heavier helmet may in fact have an advantage from the decelerative viewpoint alone. This is due to the fact that with a larger mass, for a given impact velocity, the deformation of the structure will be greater (more deceleration distance) and hence a reduced acceleration level. Obviously, there are other more important considerations, such as inertia loading of the neck in accidents not involving helmet impact, comfort, and fatigue, which limit helmet weight to as low a value as can be achieved.

When equation (33) is written in terms of drop height, then

$$a = \frac{g\left[M_F + M_H\right] h_d}{\Delta\left[M_F + M_H\right]} = \frac{h_d \cdot g}{\Delta} \qquad (35)$$

Thus, if Δ is fixed from practical considerations of total thickness, then both light weight and heavy helmets would give the same head acceleration when tested from the same drop height. The reader should, however, be cognizant of the fact that the crushable material in these helmets could not be identical, the heavier helmet requiring a material with slightly higher crushing stress.

It should be observed that equations 33, 34, and 35 are based upon an assumed rectangular force-time and hence force-deformation curve during the compressive phase of the impact.

In view of the simplicity of evaluating test results and comparing helmet performance when using the fixed anvil test method described here, it would appear to be the better method of the three possible arrangements. There are mechanical problems associated with the method, however, particularly in maintaining alignment of the impact point and the center of gravity of the head-helmet assembly with the velocity vector during impact. This is a particularly troublesome problem when head orientation is to be changed to allow impact upon several locations. Different helmets can also result in different center of gravity locations for the head form-helmet assembly. The method described in the next section eliminates this problem although it introduces an additional one, that is, the measurement of the acceleration level in the head.

IMPACT MASS MOVABLE, HEAD-HELMET ASSEMBLY FIXED

The basic mechanics for this case and the notation used in the analysis are illustrated in Figure 6.

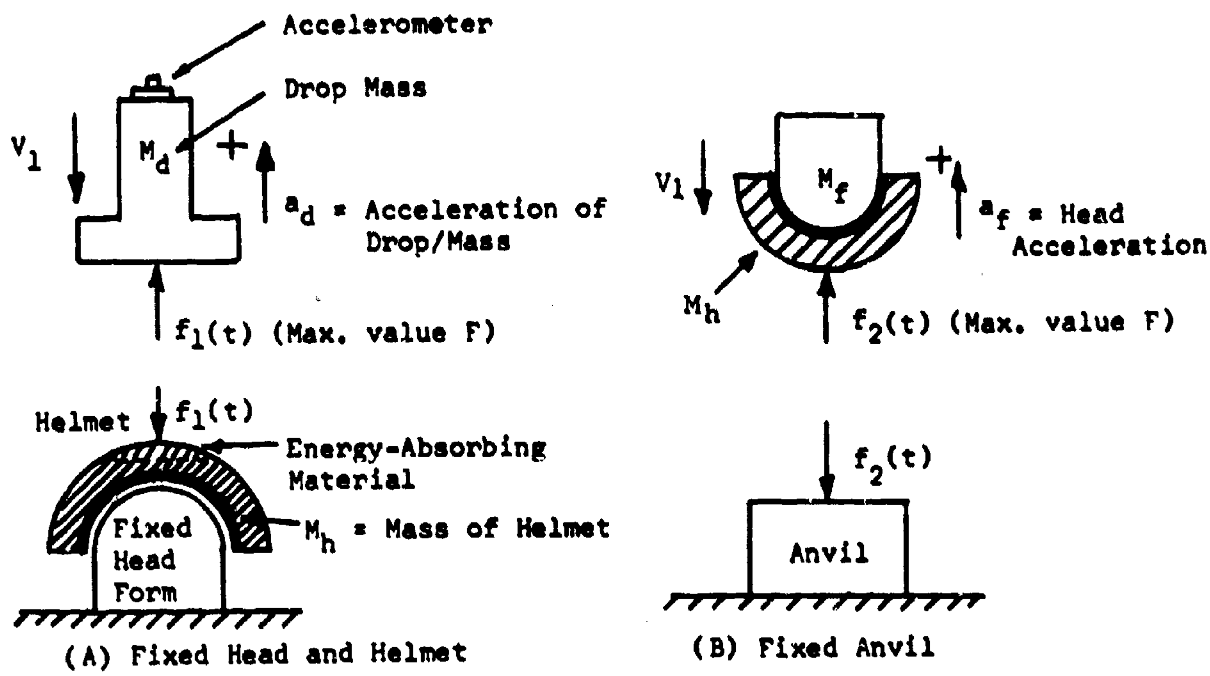

Figure 6. Comparison of Two Methods of Helmet Testing.

This method of testing is particularly convenient when it is desired to evaluate the energy-absorption capabilities of a helmet. The equations 22 through 35 are equally applicable to this method provided M in these equations is replaced by M_d. Since there is no interest in the acceleration of the impact mass in Figure 6, equations 33 through 35 are of no practical value and another approach must be taken if the equivalent head accelerations are desired in addition to the energy data. The following analysis shows that where $M_d = M_f + M_h$ (the mass of the head and helmet), the equivalent acceleration of the head a_f is very nearly the same as the recorded acceleration a_d of the drop mass. An approximate correction due to variation in the masses M_d, M_h, and M_f is illustrated.

In Figures 6A and 6B, $f_1(t)$ and $f_2(t)$ are essentially equal if appreciable energy-absorbing material is crushed and if $M_d = M_f + M_h$.

This follows since the load deformation characteristics of the material and the total energy dissipated in each case are the same. In any event, if prolonged crushing takes place at a near uniform load level, then $f_{1_{max}} = f_{2_{max}} = F$. This is true <u>even</u> if

$M_d \neq M_f + M_h$.

Now in 6B, all of the helmet is not accelerated at rate a_f since the crushed portion is not actually massless. To provide an approximate correction for the inertia effect of this portion of the system, it is assumed in Figure 7A and 7B that K_2M_h is that part of M_h accelerated in excess of a_f and that K_1a_f is the acceleration of the mass K_2M_h.

(A)

(B)

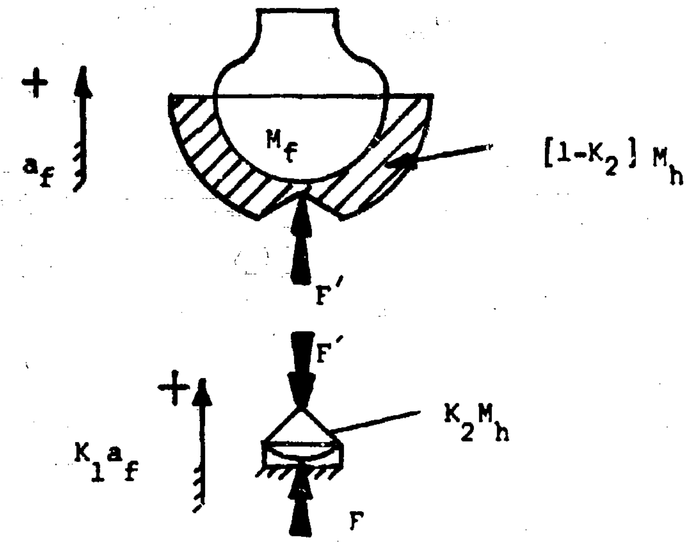

Figure 7. Free Body Diagrams for the Head-Helmet System of Figure 6B.

Applying Newton's 2nd Law, we have

From 7A : $F = M_d a_d$ (36)

From 8B : $F - F' = K_2 M_h K_1 a_f$ (37)

From 8A : $F' = \left[M_f + (1-K_2)\, M_h\right] a_f$ (38)

Solving for the ratio a_f/a_d gives

$$\frac{a_f}{a_d} = \frac{1}{\left[\frac{M_f}{M_d} + (1-K_2)\frac{M_h}{M_d} + K_1K_2\frac{M_h}{M_d}\right]} \tag{39}$$

Assuming $K_1 = K_2 = 0$ (as in the rigid-plastic models of the previous analyses) gives

$$\frac{a_f}{a_d} = \frac{1}{\left[\frac{M_f + M_h}{M_d}\right]} \tag{40}$$

which becomes unity for $M_d = M_f + M_h$ as previously stated.

The actual values of K_1 and K_2 can only be estimated for a given case, but to obtain an order of magnitude for the effect of these parameters, take what is probably an extreme case; that is,

$$K_2 = 0.2$$

$$K_1 = 3.0$$

Also, let

$$M_d = 13.5\#/g$$

$$M_f = 11.0\#/g$$

$$M_h = 2.5\#/g$$

These masses are approximately those used in the experimental tests described in this report. Then,

$$\frac{a_f}{a_d} = \frac{1}{\left[\frac{11}{13.5} + (1-0.2)\left(\frac{2.5}{13.5}\right) + (0.2)(3.0)\left(\frac{2.5}{13.5}\right)\right]}$$

$$\frac{a_f}{a_d} = 0.93$$

Thus this approximate analysis indicates that the acceleration recorded on the drop mass would have been about 7 percent higher than the equivalent acceleration of the head form in a test in which the head-helmet assembly was dropped onto a fixed anvil. This method should be valid for initial evaluation of energy-absorbing helmets; however, the movable head form method is recommended for final tests. If good experimental correlation can be obtained for the two methods, then the fixed-anvil test could be used effectively and is much easier to set up and conduct. Additional comparisons of these methods are required, however, to fully establish the correlation of the accelerations to be measured.

SIMULATION OF THE HUMAN HEAD FOR IMPACT TESTING

An accurate simulation of the human head may be useful in the determination of head acceleration limits[21]*, but it does not appear necessary, for helmet performance testing, if the acceptable acceleration-time limits of the head are known. The evaluations of the test specimens and the experimental helmets discussed in this report were accomplished on a rigid impact surface, similar to those employed by other groups who have done research in this area. However, a high density, (10 pounds per cubic foot) foamed polyurethane plastic of 0.25-inch thickness was used over the rigid head form as a simulated scalp in order that the deformation and penetration of the test specimens could be more readily observed. When pressure on the scalp reached about 200 pounds per square inch, a permanent deformation resulted so that a visual record of indentation into the scalp remained. This foamed plastic scalp cover was used with the hemispherical specimens during the initial testing, but was not used on the head form for the test of the experimental helmets, since such a device is not currently being used by other helmet-test facilities. It would be a desirable addition to a helmet-test program, although some research should be conducted to establish the optimum characteristics for this device.

*See basic report, Helmet Design Criteria for Improved Crash Survival.